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Correlation of Moisture and Oil Concentration in French Fries

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Introduction

French fry processing in the U.S. utilizes more than 30% of the potato crop (1). As part of our continuing research to develop models for computer simulation of potato processing specifically and food processing in general (2), we have begun the study of the unit operation, deep fat frying of potatoes.

Moisture and oil concentration are critical variables affecting the quality and economics of deep fat frying of potatoes. Rice and Gamble (3) presented a model which shows that the moisture content of thinly sliced (1.5 mm) deep fat fried potato chips depends on diffusion of water. The model holds for the intermediate moisture loss levels (first falling rate period) but not during the initial stages or at low moisture levels (second falling rate period). The bulk of deep fat frying of French fried potatoes (nominal 1 cm) takes place in the first falling rate period. Therefore, diffusion would be expected to be the controlling mechanism.

In an earlier paper Gamble *et al.* (4) showed there is a direct relationship between oil content and moisture content. They studied thinly sliced (1.5 mm) deep fat fried potatoes (potato chips). Keller *et al.* (5) showed that 10 mm thick deep fat fried potato strips (French fries) absorbed oil only in the outer layer. Their micrographs of cross-sections showed oil penetration is less than 1 mm. Lamberg *et al.* (6) also showed fat localization on the surface during frying of 13 mm potato strips. It is reasonable to expect that, although in a thin slice oil content is a direct function of moisture, in a thick slice it would be a much less important variable.

Obviously, time and temperature of frying are important variables for any model of frying. Pravisani and Calvelo (7) found that the actual temperature of the potato is much lower than the oil temperature. The temperature of the potato tends toward an asymptotic value of about 103°C which suggests the existence of an evaporating moving boundary within the potato piece (first falling rate period). This confirms that the diffusion model should apply to the drying during deep fat frying of French fries.

The objective of this study was to develop a model for moisture and oil content in deep fat frying of French fries.

Nomenclature

C	= concentration of diffusing component (gm water/gm potato)
D	= diffusion coefficient (m^2/min)
D_0	= frequency factor (m^2/min)
E/R	= activation energy/gas constant (°K)
k	= rate constant (gm oil/gm potato solids − min)
k_0	= frequency factor (gm oil/gm potato solids − min)
k_1	= coefficient (Newtons^{-1})
k_2	= coefficient (gm oil − gm potato/gm potato solids − gm water − min)
L	= potato strip thickness (m)
M	= moisture (gm water/gm potato)
M_0	= initial moisture (gm water/gm potato)
R	= correlation coefficient
S	= concentration of oil (gm oil/gm potato solids)
T	= temperature of frying oil (°K)
TX	= texture (Newtons)
t	= time (min)
x	= diffusion path (length)

Mention of brand or firm names does not constitute an endorsement by the U.S. Department of Agriculture over others of a similar nature not mentioned.

Materials and Methods

The raw material for the study was Russet Burbank potatoes from Aroostook County, Maine. They were harvested in October, 1989 and stored at a nominal 3°C until used. The feed rate to the pilot plant process was 225 kg/h. The potatoes were peeled in a pilot model high pressure steam peeler, DSA 45 Kunz 45-L unit with steam pressure at 1750 kPa for 15 s. Loosened peels were removed in a rod/reel washer. The potatoes were cut into strips with a nominal minimum dimension of 1 cm with an Urschel slicer model GA. A Robins Vibro-Flo washer removed the starch and sugar liberated in the cutter.

The potato strips were given the 'Philadelphia Cook', that is, they were precooked in a Rietz water blancher, model TL-36-K2210, and cooled in an Abbott screw conveyor. The blancher dwell times were set for the various experiments in the range of 5.5 to 27 min and the temperatures were controlled at various settings between 76 and 84°C. The temperatures in the cooler ranged from 33 to 39°C. Following the cooler the potato strips were normally deep fat fried in corn oil in a Dazey Products Co., model DCP-6 deep fat fryer. Due to the relative small size of the fryer, only seven potato strips were fried in each test to minimize temperature drop. Frying time was set in the range of 1 to 5 min and the oil temperature set to 201°C, 195°C, and 185°C. (In several experiments, to test the effect of overcooking on the frying operation, the potatoes were sent through a continuous atmospheric steam blancher or cooker, Robins model 20283, before frying.)

Texture measurements were made in a Food Texture Corp. testing machine, model FTA TP2 (Food texture Corp., Rockville, MD) with a model FTA-1000 force transducer according to the procedure detailed by Kozempel (8).

Moisture content of the potato strips was determined by AOAC method 7.003 (9). Oil content of the potato strips was determined by lyophilizing the potatoes and grinding to a powder. The fat was extracted from the powder with a (2:1 v/v) chloroform:methanol solvent solution.

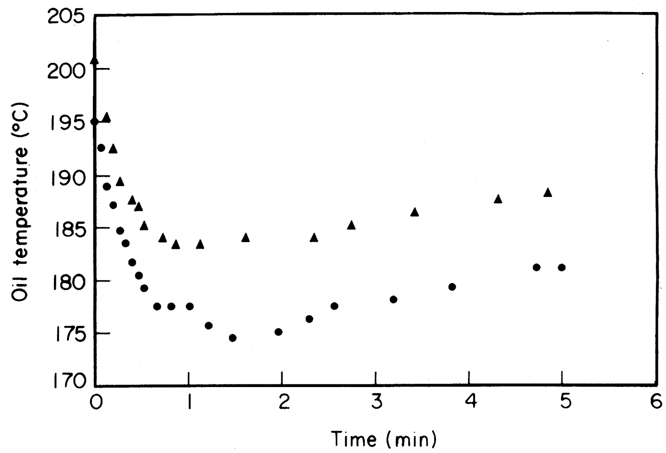

Fig. 1 Profile of the experimental frying oil temperature as a function of the frying time. ▲, 201°C; ●, 195°C

Results and Discussion

There are two major changes in composition during the deep fat frying of potatoes. The potato strips lose appreciable amounts of moisture and pick up oil from the frying media.

Moisture

It is generally recognized that deep fat frying is a drying process which accounts for the moisture loss. Is the rate controlling step diffusion controlled or heat transfer controlled? The data are not conclusive. According to Pravisani and Calvelo (7) there is an evaporating moving boundary at 103°C. The first falling rate period in air drying is characterized by evaporation of water from the surface with diffusion of water to the evaporating surface the rate controlling step. In deep fat frying the evaporating surface is at the moving boundary layer within the potato strip. It is not clear whether the rate controlling step is energy transfer to the potato strip, or diffusion of water and/or vapor through the potato strip.

If diffusion is rate controlling then Eqn [1] applies. If energy transfer controls then the equation is of the same form but relates the change of temperature with time with the rate of change of the temperature profile using a thermal diffusivity constant.

The prevailing opinion, Pravisani and Calvelo (7) and Rice and Gamble (3), is that diffusion of water vapor is rate controlling. We agree. The moisture loss should correlate with Fick's law of diffusion;

$$\delta C/\delta t = D\, \delta^2 C/\delta x^2 \qquad \text{Eqn [1]}$$

Treating French fry cut potatoes as an infinite slab, the series expansion solution to Fick's law can be found in Newman (10).

$$M/M_0 = 8/\pi^2[\exp(-D\pi^2 t/L^2) + 1/9 \exp(-9(-D\pi^2 t/L^2)) + 1/25 \exp(-25(-D\pi^2 t/L^2)) + \cdots] \qquad \text{Eqn [2]}$$

Only the first term is significant. The variable L should be the diffusion path. Does the diffusion path correspond to the path of water diffusion from the center of the potato strip to the boundary layer or the vapor diffusion path from the boundary layer to the surface which includes the crust at the surface? To complicate the situation, these dimensions change during the drying process. To simplify we used the nominal thickness of the potato strip.

As the potato strip dries, the structure, composition and temperature of the diffusion path changes affecting the value of the diffusion coefficient. Oil diffuses into the surface volume forming a crust on the surface. The interior of the potato loses

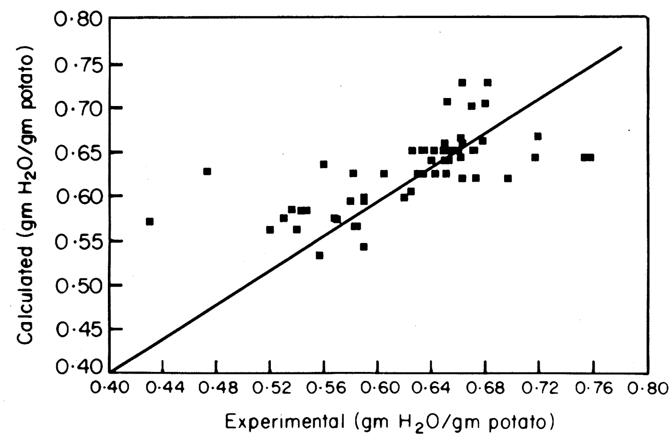

Fig. 2 Comparison of the correlated and experimental water content of French fries (gm water/gm potato, wet basis); $Y = X$ reference line

moisture and the temperature of the potato rises toward 103°C. We found that we could correlate the change in the diffusion coefficient with the oil temperature using Eqn [3].

$$D = D_0 \exp(-E/RT) \qquad \text{Eqn [3]}$$

In our experiments the oil temperature was not constant. As shown in **Fig. 1**, the oil experiences an initial rapid drop with a slow recovery. The temperature never returned to the initial temperature during the individual frying experiments.

Using 57 data points at various times and temperatures we correlated the data with Eqn [2] and [3]. To evaluate the equations we calculated the experimental data at finite time increments of 0.1 min and used the temperature profiles in **Fig. 1** to determine the temperature at any time. The data were correlated using a least squares fit.

The value for D_0 was 1.39E-9 m^2/min and for E/R was 751°K. Since many different parameters were used during the experiments, we plotted the correlated or calculated values against the experimental data in **Fig. 2** (R = 0.73). The average absolute error in moisture value between calculated and experimental was 0.033 gm moisture/gm potato (wet basis).

Oil

Obviously, fry time and temperature are important parameters for the oil absorption during frying. Initial experiments showed a linear increase in oil content with time (holding other contributing parameters essentially constant) and an exponential increase with temperature. The temperature effect was

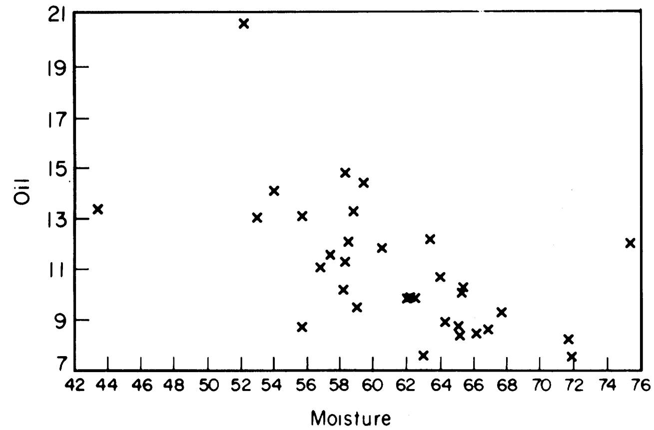

Fig. 3 Plot of the trend of oil content (gm oil/gm potato, moisture free basis) of French fries as a function of moisture content (gm water/gm potato, wet basis)

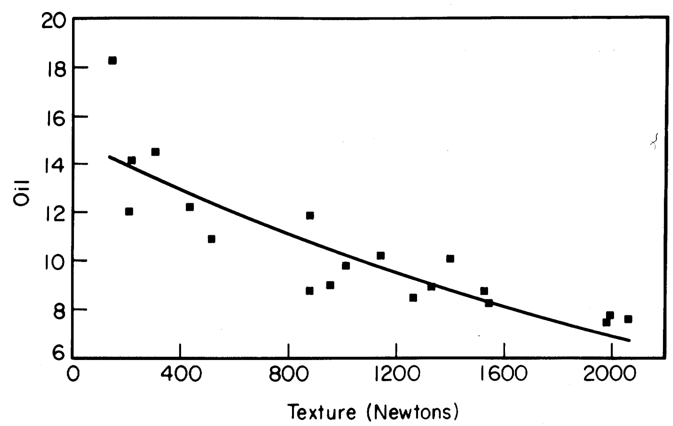

Fig. 4 Plot of the trend of oil content (gm oil/gm potato, moisture free basis) of French fries as a function of texture

assumed to follow an Arrhenius relationship. But, are there other important variables?

Gamble *et al.* (4) showed there is a direct relationship between moisture and oil content. **Figure 3** plots oil content against moisture content. Although the data are highly confounded with time and temperature, there is an apparent relationship. During the study, it became apparent that the texture of the potato strips entering the deep fat fryer was important. **Figure 4** plots the oil content after 2 min fry time at an initial oil temperature of 201°C *vs.* texture of the entering potato strips. There is a definite relationship. We correlated the oil/texture data using exponential Eqn [4],

$$k = k_0 \exp(k_1 TX) \qquad \text{Eqn [4]}$$

The curvilinear correlation coefficient was 0.5. To account for the moisture effect, we added a term for moisture to Eqn [4] to get Eqn [5].

$$k = k_0 \exp(k_1 \times TX) + k_2(M) \qquad \text{Eqn [5]}$$

where: $k_0 = 0.321$
$k_1 = -4.18E\text{-}3$
$k_2 = 0.281$

Since the oil content varied linearly with fry time, we tried a zero order kinetics model, Eqn [6], to correlate the data using Eqn [4] to establish the value of the rate constant, k, in the model.

$$dS/dt = k \qquad \text{Eqn [6]}$$

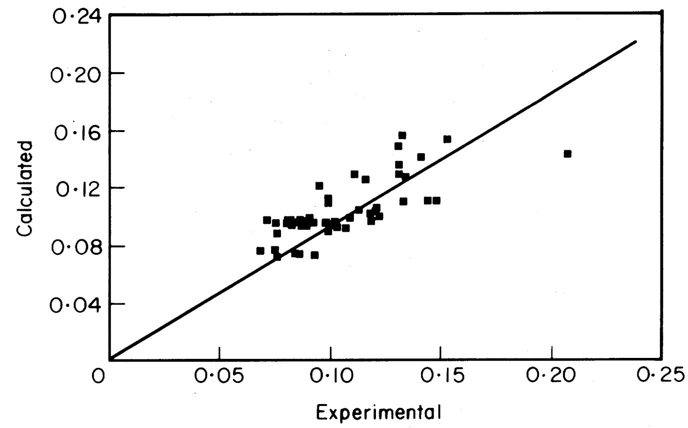

Fig. 5 Comparison of the correlated and experimental oil content of French fries (gm oil/gm potato, moisture free basis); $Y = X$ reference line

Assuming the rate constant, k, follows an Arrhenius relationship, we added an exponential term for temperature (E/R = 1038°K). The final equation is;

$$dS/dt = [k_0 \exp(k_1 \times TX) + k_2(M)] \exp(-E/RT) \qquad \text{Eqn [7]}$$

The data were correlated using a least squares fit to determine the values of all coefficients plus the best value for the constant of integration. The constant of integration was 0.05. Since many different parameters were used during the experiments, we plotted the calculated values against the experimental data in **Fig. 5** ($R = 0.70$). The average absolute error in oil content between calculated and experimental was 0.013 gm oil/gm potato (moisture free basis).

Accuracy

To better appreciate the accuracy of the correlations relative to the experimental errors and normal raw material variation, we fried three sets of five potato strips each. Then, we determined moisture and oil content for each strip. At the 95% confidence level, the experimental data varied by ±0.049 gm water/gm potato (wet basis) and ±0.0165 gm oil/gm potato (moisture free basis). Lamberg *et al.* (6) reported standard deviations in oil data ($n = 5$) of 0.014 and 0.008 gm oil/gm dry solids at 5 and 1 min fry times. The errors in moisture and oil of 0.033 gm water/gm potato (wet basis) and 0.013 gm oil/gm potato (moisture free basis) associated with the correlations were of the same approximate magnitude as these experimental errors.

To test the correlations, we used the equations to predict the oil and moisture content of fries. For 16 values of oil the error in the prediction was 0.014 gm oil/gm potato (moisture free basis). For 15 values of moisture the error was 0.030 gm water/gm potato (wet basis). These values indicate that the equations are sufficiently accurate to predict oil and moisture content.

Conclusion

A diffusion model was used to correlate the drying or moisture content of French fries during deep fat frying. A zero order model was used to calculate the oil absorption. The models predict with sufficient accuracy the concentration of oil and water in French fries. We anticipate the combined model can form the basis of a model for simulating the deep fat frying unit operation for French fries.

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